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Review

Overview of Fire Prevention Technologies by Cause of Fire: Selection of Causes Based on Fire Statistics in the Republic of Korea

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Abstract: Every year, diverse types of safety accidents cause major damage to human life and property. In particular, failure to suppress safety accidents caused by fires during the early stages can lead to large-scale accidents, which in turn can cause more serious damage than other types of accident. Therefore, this paper presents an analysis of the prevailing research trends and future directions for research on preventing safety accidents due to fire. Since fire outbreaks can occur in many types of places, the study was conducted by selecting the places and causes involved in frequent fires, using fire data from Korea. As half of these fires were found to occur in buildings, this paper presents an analysis of the causes of building fires, and then focuses on three themes: fire prevention based on fire and gas detection; fire prevention in electrical appliances; and fire prevention for next-generation electricity. In the gas detection of the first theme, the gas referred to does not denote a specific gas, but rather to the gas used in each place. After an analysis of research trends for each issue related to fire prevention, future research directions are suggested on the basis of the findings. It is necessary to evaluate the risk, select a detection system, and improve its reliability in order to thoroughly prevent fires in the future. In addition, an active emergency response system should be developed by operating a fire prevention control system, and safety training should be developed after classifying the targets of the training targets appropriately.

Keywords: fire prevention technology; fire; gas detection; cable; control system; next generation electricity; ESS; energy storage system; safety

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1. Introduction

Various types of safety accidents occur on a frequent basis, causing serious damage to human life and property. Damage to humans due to such accidents can range from minor injury and disability to maiming and even death, while property damages can range from minor damage to individual properties to devastation of vast housing areas industrial sites. There are various types of safety accidents, the most typical being accidents involving falls, electric shocks, and fires.

Failure to suppress safety accidents caused by fires at the early stage can lead to large-scale accidents, which in turn can cause more severe injury and property damage than other types of accident. A fire in a building with a structure similar to a subway has many fatal accidents, due to the closed location [1]. In offshore structures, half of the accidents are caused by fire, and it can be confirmed that about 40% of people died in accidents where the fire occurred [2]. In addition, since safety accidents due to fire can occur at any time in diverse places, such as homes, residential and industrial sites, vehicles, vessels, aircraft, and special material handling facilities, the necessity for accident prevention is growing.

Corporations, schools, and research institutes are trying to develop and apply prevention systems that can detect and preemptively respond to fires at an early stage, in order to prevent fires. With the recent development of the IoT (Internet of things) and communication networks, accidents can be responded to in a smart way by developing models that can collect fire-related data from areas devoid of people or areas that are difficult to access, and detect fires based on the collected big data. Nevertheless, it is expected that the frequency and risk of fires will not fall rapidly, given not only the potential failure of aging facilities but also the complexities and risks inherent to the new energy sources that are being adopted by eco-friendly cities.

Therefore, this paper presents an analysis of ongoing research trends and future directions for research on preventing safety accidents caused by fire. Since the scope of fires that can occur in diverse kinds of places, including buildings, vehicles, hazardous material manufacturing facilities, vessels, and aircraft, is too wide to cover in this paper, the scope is limited to building fires, which account for the majority of all fires. This paper also includes an analysis of research trends and suggests directions for research in consideration of the causes of building fires. That is, this paper selects items that can cause a fire in a place called a building, and analyzes the research trend for preventing fires caused by each item.

A variety of factors can cause a fire in a building, including electrical or mechanical factors, gas leaks, chemical factors, negligence, acts of arson, and so forth. When analyzing the causes, the items that were researched with similar measures were grouped and analyzed in this paper. There are three classified items: fire prevention by detecting fire and gas; fire prevention in electrical appliances; and fire prevention for next-generation power.

The first item entails fire prevention by detecting fire and gas, which involves detecting the causes of gas leaks and chemical factors in order to identify the risk of fire at an early stage and take preemptive measures. This also helps with the prevention of general fires, since early fire status can be detected and notified to the user by the sensing of heat and light in addition to gas. The research trends of this item are analyzed in this paper.

The second item entails fire prevention by reducing the fire risk of electrical appliances. Today, electricity is an essential source of energy in all of our lives, and households and industries operate numerous appliances using electric power. As such, fire outbreaks can occur due to aging electrical appliances, poor management, or simple carelessness. Much research is being conducted to analyze the causes of fires in electrical appliances in order to prevent them and to find methods of alleviating the risk. This paper also features an analysis of the research trends of this item.

The last item involves fire prevention in the use of next-generation electricity sources. The main types of next-generation power systems include solar systems that generate electricity from the Sun; ESSs (Energy Storage Systems) that can store electricity; and hydrogen fuel cells. The listed energy sources are basically outputted as direct current.

Direct current requires a higher current to have the same effect on the human body as 60 Hz [3]. However, the risk of an arc due to a direct current fault is very high, as experimentally confirmed [4]. In addition, the necessity for a fire detection and prevention system to ensure the safe use of next-generation power sources is emerging, as cases of fire in solar power systems and ESSs have been reported [5–8].

The necessity for such a system is also emerging with regard to hydrogen fuel cells that use hydrogen, a hazardous material. Research institutes are endeavoring to develop and introduce a fire prevention system in consideration of the characteristics of the next-generation power system. This paper includes an analysis of the research trends for this item; in conclusion, it also proposes a future direction for research based on the findings of the analysis of the research trends for the three above items. This paper is organized as follows: Section 2 introduces the present condition of fires based on an analysis of fire statistics in S. Korea; Section 3 analyzes the main research trends by classifying the causes of building fires, which account for the majority of local fires; Section 4 proposes a future research direction for fire prevention; and, lastly, Section 5 presents the conclusion.

2. Data-Based Analysis of the Fire Outbreak Status in the Republic of Korea

It is difficult to analyze the causes of fires for all scopes and suggest a research direction, because fire outbreaks occur in diverse types of places due to a wide range of causes. However, it can be effective to select the scope and focus when researching fire prevention. Therefore, this paper selected places where fire outbreaks occur and analyzed the causes of fires in such places, and established a future direction for research on fire prevention based on the findings.

Data on fires in the Republic of Korea (ROK) and data provided by the National Fire Agency (ROK) were used to determine the research scope of this paper. First, this paper discusses the risk of fires and the need for fire prevention by visualizing the data on the number of local fires, losses of life and property, and breakout frequency by province. The places where fire outbreaks occur frequently were selected by analyzing statistical data on fires, considering both place and cause, to understand the major causes of fires in those places.

Figure 1 shows the number of fires and loss of life that occurred in ROK from 1996 to 2021. The broken line graph in Figure 1 shows the number of fires, with the bar graph showing the loss of life. The loss of life is expressed by the gray and yellow bar graphs after dividing it by the number of deaths and number of injured people.

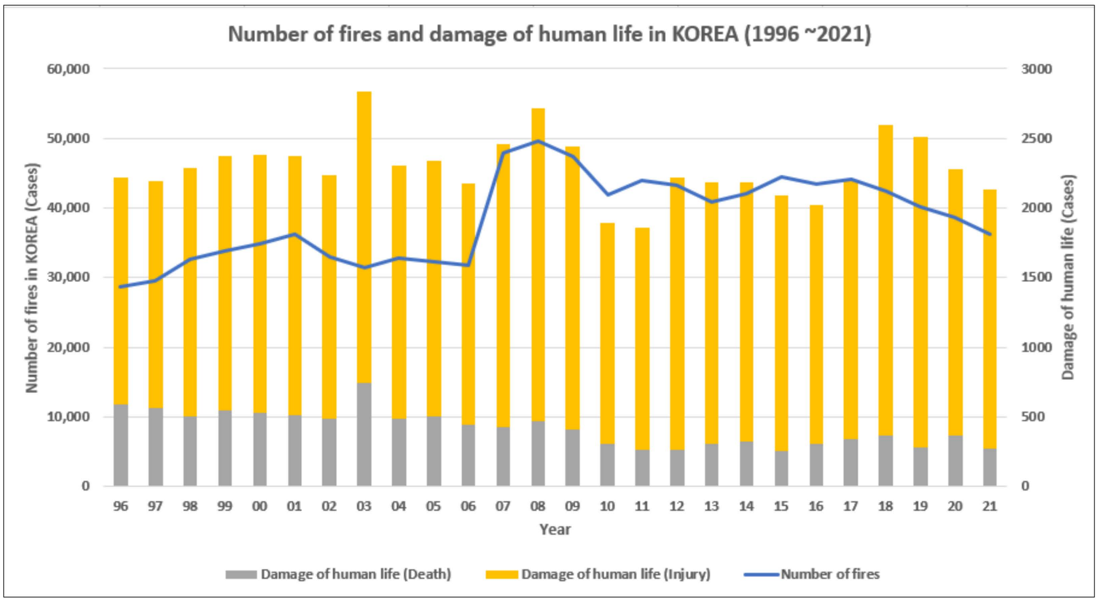

Figure 1. Number of fires and damage to human life in ROK (1996–2021).

Numerous fire outbreaks occur every year (an annual average of 38,532 fires), and 2289 persons are killed or injured every year [9] (with 419 people killed and 1871 injured each year on average).

Figure 2 shows the number of fires and loss of property in ROK during the years 1996 to 2021. The broken line graph in Figure 2 shows the number of fires, with the bar graph showing the loss of property. Despite the fact that the bars do not move in proportion to the number of fires occurring each year, it clearly shows that property damage caused by fires has continued to increase over 26 years [9] (1996–2021).

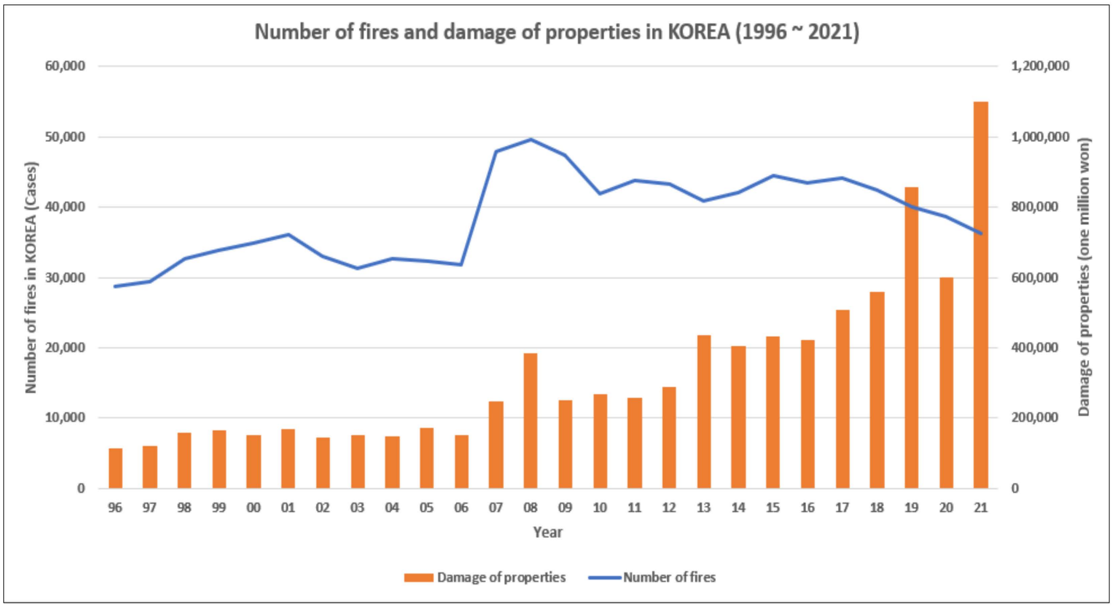

Figure 2. Number of fires and property damage amount in ROK (1996–2021).

Figure 3 visualizes the statistics on fires by place as a program for analysis. Despite the fact that data by place from 1996 to 2007 have been published, about 25% on average is missing for the data column. As a result, the graph was created using data from 2008 to 2021. In the data concerned, labels 'residential' and 'non-residential' refer to fires that occurred in buildings. It can be seen that the first occurred in the building, accounting for an average of 62.7% of the total during the period covered by the graph. as the majority of fire outbreaks occur in buildings, research trends were analyzed with a focus on building fire prevention.

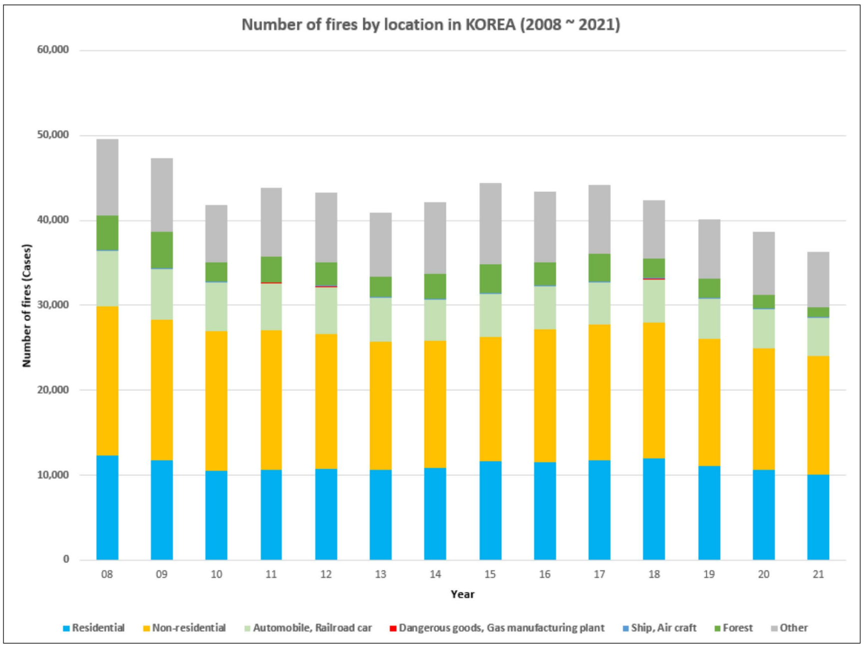

Figure 3. Number of fires by location in ROK (2008–2021).

Figure 4 visualizes data as a graph for analyzing the causes of fires. It can be seen that the fire rate due to negligence accounts for about half of the total. As gas leaks and fires caused by chemical factors, in addition to negligence, are the factors that can be prevented by fire and gas detection, they were selected as the first topic of the trend analysis.

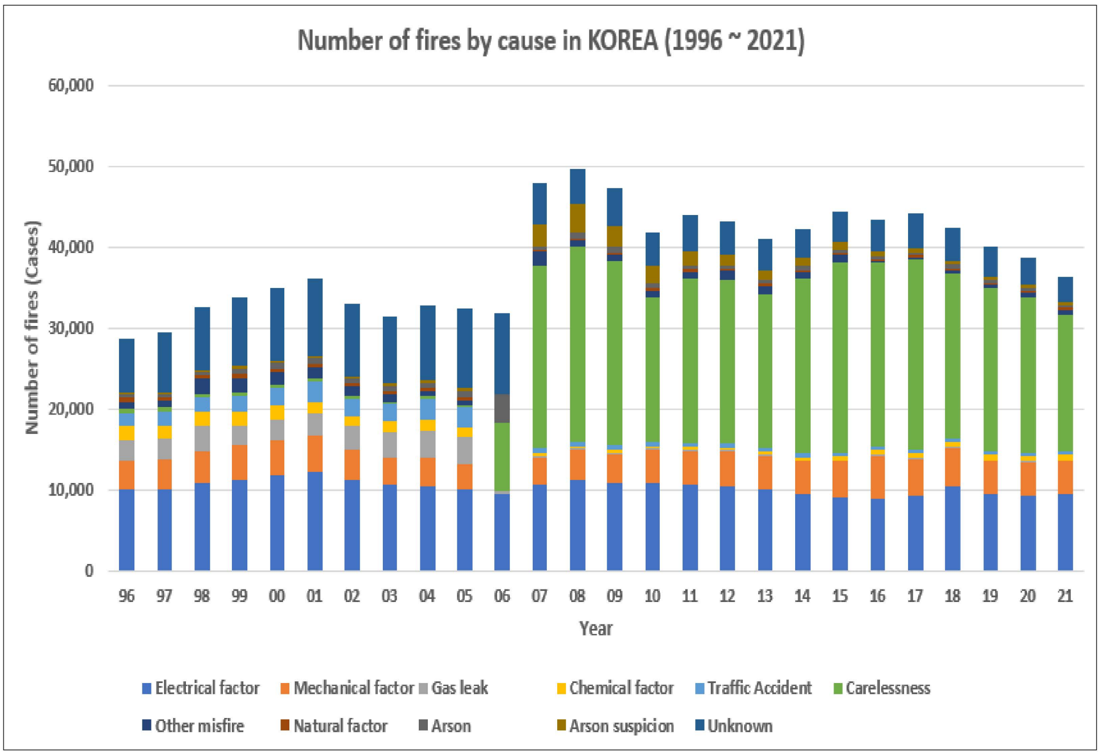

Figure 4. No. of Fires by Cause in ROK (1996–2021).

In addition, fires due to electrical factors account for 27.4% of the total number of fires on average, while those caused by mechanical factors account for 10.5% of the total number of fires on average. As mechanical factors partially include the causes of mechanical faults/malfunctions of electrical devices, such as malfunctions of switches and electrical equipment, it is suspected that fires involving mechanical equipment actually account for one-third of such fires. Therefore, fire prevention in electrical appliances was selected as the second topic of the trend analysis.

The electrical appliance selected as the second topic has various product groups, and the direction of research trend analysis varies depending on the characteristics of the product group. To analyze the product groups that account for a high percentage of the total number of fires in electrical equipment, fire statistics were analyzed according to product types, and are shown in Figure 5. The data applied in Figure 5 occurred in S. Korea over 5 years (2017–2022), and only fires due to electrical factors of electrical equipment were specified. Given that most fires occur in the order of wiring, electrical, seasonal equipment, and kitchen appliances, the research trends for the four product groups with high fire frequency were analyzed. For seasonal devices, air conditioners and heating wires appeared in the highest order of causes of fire, but the analysis focused on heating wires, because the type of heating wire is missing in the four product groups.

Lastly, a number of new electric technologies (i.e., solar power, energy storage system, and hydrogen fuel cells) that are currently being developed as next-generation power sources were selected as the third topic of the fire prevention trend analysis, because they carry a higher risk of fire than existing electric equipment.

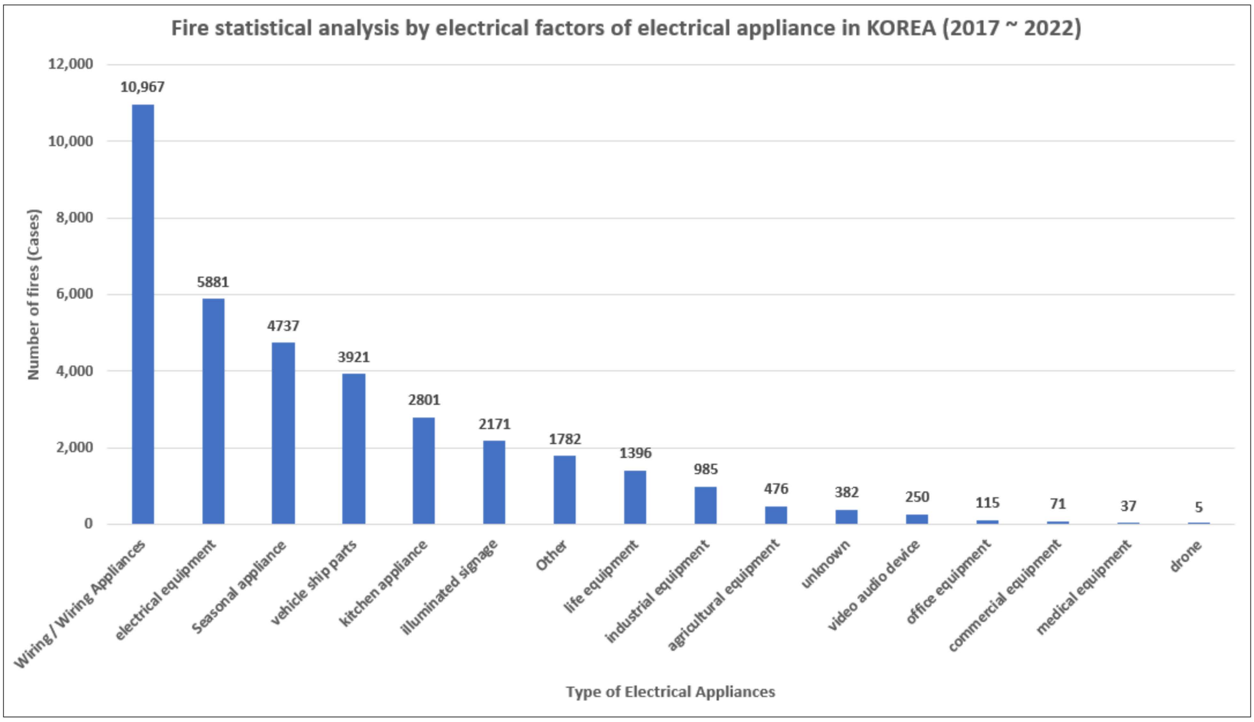

Figure 5. Fire statistical analysis by electrical factors of electrical appliances in ROK (2017–2022).

3. Analysis of Research Trends for Fire Prevention by Cause

By classifying and grouping fire causes, three research trend analysis topics were selected, with the selection process being shown in Figure 6. The research trends for each of the three selected themes were analyzed and described below.

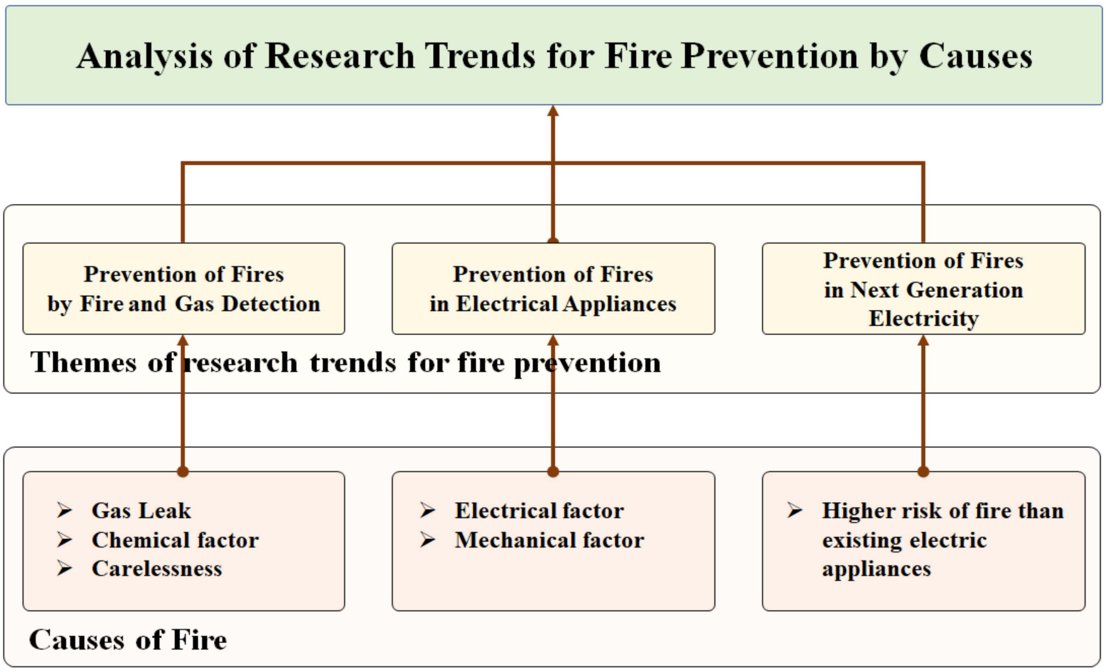

Figure 6. Analysis of research trends for fire prevention by cause.

3.1. Fire Prevention by Fire and Gas Detection

First, the trend of fire prevention by fire and gas detection was analyzed. Technologies that fall under this theme include gas detectors, smoke detectors, flame detectors, and video analysis. The main research areas for detector types include both improvements in the performance of detection sensors and of testing methods and the development of analysis algorithms in image analysis technology. The main technologies and research areas are shown in Figure 7, along with the research trends for each technology described below.

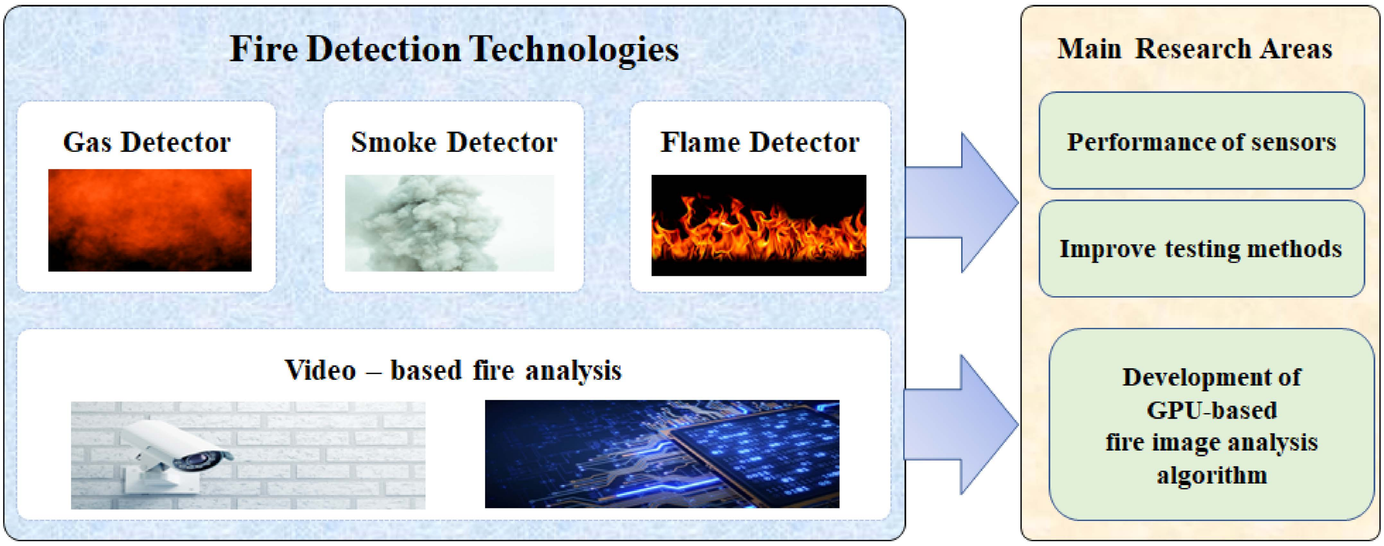

Figure 7. Prevention of Fires by Fire and Gas Detection.

Gas detectors are widely installed at all kinds of sites and facilities as a means of preventing fires caused by gas leaks, chemical factors, and carelessness. The "gas" mentioned does not refer to a specific gas, but rather to the type of gas used in each place or method. For example, a gas detector in a kitchen uses liquefied petroleum gas means a sensor for measuring the concentration of LPG, and a gas detector in a kitchen uses liquefied natural gas means a sensor for measuring the concentration of LNG.

A gas detector measures gas leaks caused by mechanical or gas pipe failures, and stops the apparatus or blocks the pipe when it detects a gas concentration above a certain level. This method also prevents fires by generating a visible and audible alarm. When installing gas detectors inside a building, it is advisable to select a model suitable for the type of gas in use and choose the installation site in consideration of the characteristics of the gas.

LPG (Liquefied Petroleum Gas) is generally used in South Korean homes, along with LPG leakage detection systems installed accordingly. In the case of LPG sensors, Shobi Bagga et al. studied a method of applying the SnO_2 thin-film transducer and the ASIC (application-specific integrated circuit) [10], while Anindya Nag et al. [11] conducted research on the encouraging response time by applying a novel strategy. Abdul Hannan et al. [12] also conducted research on the development of a system for checking LPG leakage detection systems using an IoT (Internet of Things) device, which was designed for use in the field according to the UK's occupational health and safety standards. Recently, the use of LNG (Liquefied Natural Gas) fuel or hydrogen fuel cells in buildings to meet eco-friendly requirements has increased markedly, with detection systems being under development to protect the safety of the overall system.

It is also important for the systems to be capable of detecting and responding to fires at an early stage, because it could significantly reduce the risk of fires, in addition to fire prevention by detecting gas. Since early detection is an effective way to save lives and reduce property damage, it is also being applied to prevent fires from other causes [13].

Smoke detectors are widely used to detect fires. Smoke detectors, which emit a fire warning signal after detecting smoke from flames, were first developed in the 1960s and applied to residential areas, with efforts being made to decrease the risk of fire by installing smoke detectors. For example, Greibell [14] published research on a system that connected a safety warning device to existing smoke detectors. This system automatically generated an audible alarm by activating an auxiliary alarm device whenever the smoke detector detected smoke, which resulted in cost savings due to its compatibility with existing smoke detectors, as well as enhancing the fire prevention effects.

Geiman and Gottuk [15] also conducted research on providing a quantitative basis for accurately evaluating external critical optical smoke density to improve the measurement accuracy of smoke detectors. They analyzed optical smoke density data and compared it to the alarm threshold value recommended in the literature, so that it could be used as a guide.

On the other hand, research was also conducted to analyze the results of efforts to reduce the risk of fire by installing gas detectors in the home. Montgomery County in Maryland state, U.S.A., enacted the first-ever law to mandate the installation of smoke detectors in all homes. McLoughlin et al. [16] investigated the installation status of sensors in private homes 5 years after the enactment of mandatory installation and the normal operational status of the sensors. They also analyzed fire data over a 12-year period, finding that gas detectors actually reduced the risk of fire, and then published the results in a thesis. In addition, Gorman et al. [17] published a case study in which the smoke detector installation rate was increased by introducing a smoke detector giveaway program, which increased the operation rate of installed detectors. Their research was successful in that they proposed a method of reducing the risk of fire beyond warranting legal measures.

Rohde et al. [18] published the results of their research, which indicated that the installation of gas detectors in buildings had a positive impact, resulting in fewer fire accidents. They observed that the number of deaths in households fitted with gas detectors was half that of households without any gas detectors. However, they were unable to discover a significant correlation between the fire injury reduction rate and gas detector installation rate, and planned to analyze the correction through further research.

In addition to smoke detectors, flame detectors are also widely used for fire detection in the early phase. The flame detector detects fire by analyzing multiple wavelengths generated by flickering flames. Thuillard [19] discovered certain properties that can distinguish flames using the flickering spectrum of flames and developed a new algorithm by combining wavelet and fuzzy technology. In addition, Erden et al. [20] developed a detector that detects flames using a Markovian decision algorithm based on a PIR (pyro-electric infrared) sensor and published the results, showing its ability to detect flames with greater accuracy than other models.

There was also research aimed at developing a new type of sensor, rather than the commonly used types of sensors, and some studies announced the improvements over existing sensors achieved in experiments. Kriiger et al. [21] developed a hydrogen sensor to detect fires faster in the early stage. They found that their sensor could be applied to various fire scenarios at the early stage by detecting hydrogen. Li et al. [22] developed the long-range Raman-distributed fiber temperature sensor (RDFTS) and presented the temperature early warning model (TEWM), which detects and warns of the fire at the early stage.

Recently, frequent attempts have been made to apply image quality and analysis technology to fire detection as its level rises sharply. Jinghong et al. [23] announced that they were conducting research on how to detect smoke and monitor fires in real time by capturing and analyzing thermal images using FPGA (Field Programmable Gate Array). In addition, Ye et al. [24] developed and proposed an algorithm for detecting smoke and flames from camera images simultaneously, while also conducting experiments to verify its superiority over existing detectors.

Alternatively, Matsuyama et al. [25] proposed an active thermal imaging system based on THz electromagnetic waves, and verified, through experiments, that fires can be monitored while less affected by smoke.

As GPU (Graphic Processing Unit) technology develops rapidly, the accuracy and speed of smoke detection based on images are improving. Filonenko et al. [26] published the results of their research, showing that smoke can be detected four times faster than recent image analysis technology by applying CUDA (Compute Unified Device Architecture), one of the main GPGPU (general purpose computing on graphics processing unit) technologies. In addition, Chen et al. [27] proposed a new algorithm for the purpose of fire detection. The algorithm combined fire segmentation and multi-feature fusion of fire and demonstrated a slightly higher level of precision than the deep learning method. Cao et al. [28] researched the application of a new EFFNet (Enhanced Feature Foreground Network) algorithm to image analysis in order to detect smoke by predicting its sources, and suggested that further research, combining accurate smoke detection with physical characteristics, is needed.

The fire detection method based on image analysis has excellent detection ability in the early stage, so it is widely used outdoors, not inside buildings. One example is a study in which flame detection technology using YOLOv4 among deep learning techniques is applied to a smart city environment [29].

In fire prevention through fire and gas detection, research trends for various types of detectors were analyzed. First, the gas detector was analyzed for the LPG detector. Research has been conducted on a gas sensing system to not only improve the response time for gas measurement, but also apply it to check gas leaks in IoT equipment [10–12]. A study was conducted to provide a guide for performance measurement of smoke detectors, as well as another study which confirmed fire risk mitigation according to the installation of smoke detectors [13–18].

A flame detector and video-based measurement method have been studied for detecting a fire via a flame. The flame detector was researched with the intention of developing an algorithm that analyzes the wavelength of flame, and it was confirmed that accuracy was improved compared to the existing model [19–22]. A video-based measurement method was studied to analyze images based on thermal images, while research has been conducted with the intention of increasing the accuracy of smoke and flame detection and shortening the response speed, besides other research conducted to apply new machine learning techniques to improve the accuracy of smoke detection. In order to improve the response speed for smoke detection, a study was conducted to apply GPGPU (general purpose computing on graphics processing unit), and performance four times faster than before was announced [23–29].

3.2. Fire Prevention in Electrical Appliances

The second most common cause of fires is the kinds of electrical appliances that are commonly used in buildings. Figure 8 describes the cause of fire in electrical equipment and the research direction for prevention.

A fire may break out in an electrical appliance in use due to mechanical failure; an arc due to electrical failure; or heat due to overload. Special attention is required concerning electrical appliances used for heat generation, because a fire can result from a malfunction or fault defect. The authors of this paper are trying to analyze the research trends for prevention of the arc due to electrical failures and the prevention of fires due to electrical equipment used for heat generation.

Many studies have been conducted to measure and test the arc due to electrical failure. Park et al. [30] developed an algorithm to measure the series arc for preventing electrical fires. They proposed a method of measuring the AC voltage that includes the arc voltage in order to distinguish a series arc in a normal state and used a phase shift algorithm for applications with a non-linear load.

Technology for preventing fires by measuring the arc fault was also researched. Zhen et al. [31] introduced a mechanism for the arc fault and conducted research on a method of detecting arc faults and classifying the detected arcs. They also presented the trends of arc fault studies to prevent electrical fires and lay foundations for establishing the related standards. Qi, Zi-bo et al. [32] designed simulation equipment that could create the arc fault of the product to use for research or verification tests. They contributed to the prevention of fires caused by the arc fault by developing such equipment.

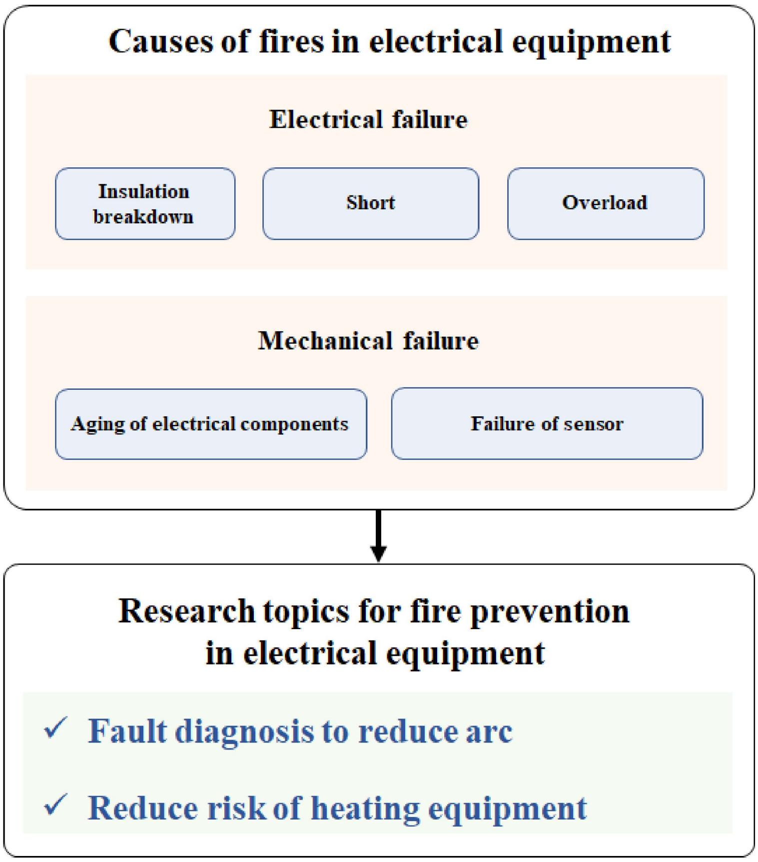

Figure 8. Research trends for fire prevention in electrical equipment.

Electrical appliances used for heat generation include induction cookers used in the kitchen, electric heaters for heating, and heating wires for preventing freezing. Although we might think that induction cookers are safe, Wong and Fong [33] proved the risks associated with induction cookers by conducting experimental research, thus raising the need for an appropriate safety device. Hong et al. [34] also proved the risk of fires by creating an experimental scenario in which inflammables were brought into contact with the front of the heating apparatus of an electric heater, and proposed a method of fire prevention.

Meanwhile, among the diverse electrical appliances used for heat generation, anti-freeze heating cables (self-regulating heating cables) are mainly used to protect various pipes and tanks from freezing in winter, including water pipes, water storage tanks, and water meters [35]. The use of self-regulating heating cables is increasing due to their ease of installation and low maintenance costs, but the number of fires caused by these cables is also increasing proportionally. The heating wires used for freeze protection include self-regulating heating, belt heater, and constant wattage heating cables [36].

Among the three types of anti-freeze heating cables, self-regulating heating cables are frequently used to protect water pipes and tanks from freezing in winter, because they can be installed conveniently and maintained cost-effectively. due to their low price, while being cut to the desired length.

Erickson [37] studied a reliable and cost-effective method of electrically heating pipelines with self-regulating heating cables, based on a method of using the cable resistance of self-regulating cables for pipeline temperature feedback and control.

Lardear [38] conducted research control of self-regulating heating cables for use in pipeline heating applications, and also researched a method of controlling temperature without conventional sensors. Lee and Lee [39] researched the effect of reducing electrical energy by developing a temperature controller for anti-freeze heating cables, which also detected the temperature of the pipe interior at the same time.

Wang et al. [40] researched the structure and applications of CB crystal fluoride resin alloy in self-regulated heating cables. Bao Guo et al. [41] researched the application of self-regulating heating cables in order to cure concrete in winter, and also proposed self-regulating heating cables and new concrete curing methods. Meanwhile, Khrenkov [42] researched the influence of environmental conditions on the characteristics of self-regulating cables.

Many studies are currently underway to analyze fire risks and prevent fires with anti-freeze heat wire, which is widely used in many everyday applications. Walter [43] discovered, in his study titled "Extreme Overheating in Self-Regulating Heating Cables", that saltwater infiltration due to mechanical damage to the cable or leaking terminations causes cable breakage.

Lee and Park [44] researched the possibility of ignition of anti-freeze heating cables and determined the degree of possibility based on four causes of ignition of anti-freeze heating wire short circuit, heat storage, or poor contact. In their paper, titled "Study on Short-Circuit Fire Risk of Anti-Freeze Heating Wires", Lim et al. researched the risk of short-circuit fires by comparing series-type heating wires with constant temperature wires. According to their paper, when a series-type heating wire short-circuits, the current flow is three times higher, yet the temperature of the covering was observed to be lower than the rated temperature.

However, the risk of fire due to heat storage has increased with the passage of time. One paper [45] showed that the risk of fire due to the arc was high when a constant temperature wire short-circuited and the flow of current exceeded 30A. In a paper titled "Study on the Heat Flow Characteristics of Natural Convection in a Sealed Circular Pipe with Anti-Freeze Heating Wire", Seo et al. [46] analyzed the heat flow characteristics in a sealed circular pipe according to the location of the heating wire. As a result, they proved that the heat transfer characteristic of one heat source was best at $\theta = 135°$, and that heat transfer efficiency could be improved at $\theta = 135°$ and $\theta = 180°$ when there are two heat sources.

Meanwhile, some experimental studies have been conducted to analyze the fire hazard and ignition cause of the anti-freeze heating wire. For instance, Lee and. Ha [47] analyzed the causes of ignition using traces of fire by conducting experiments with a focus on constant temperature wires. Min and Song [48] also analyzed the risk of ignition and fire based on an experimental study of electric heating wires. In addition, Lee et al. [49,50] analyzed the risk of fire by running the temperature rise test for each scenario involving anti-freeze heating wire, and pointed out the necessity of strengthening the standards for fire prevention.

Fire prevention analysis for electrical equipment was conducted for arc faults and electrical equipment for heating purposes. In order to prevent fires caused by arc faults occurring in electrical equipment, arc faults were measured via simulation or a method of measuring arc faults was studied [30–32]. For electric devices for the purpose of generating heat, the cause of the temperature rising from the normal operating state was analyzed, with the risk verified through experiments [43–46]. In addition, the cause of ignition was analyzed by experimentally confirming the change in temperature rise according to the installation state of the heating wire [47–50].

3.3. Fire Prevention in Next-Generation Electricity

In general, electricity used to operate electrical appliances is generated using fossil fuels, such as coal and petroleum. These fuels affect the environment and climate by emitting carbon dioxide during power generation. In recent years, many countries around the world have recognized the severity of carbon emissions and moved towards better regulation. Furthermore, many countries and corporations are developing, demonstrating, and applying eco-friendly energy to the field in response to tightened regulations. They widely use solar power generation technology, which was initially developed and demonstrated many years ago, because it can utilize the remaining space outside a building. They are also trying to integrate solar power technology with an energy storage system technology that can recharge batteries when there is excess power, for later use. However, the fire risk of solar power and energy storage system technologies is greater than other power generation systems, as they use high voltage DC. As many studies aimed at reducing the risk of fires and explosions are currently underway, this paper analyzes the related research trends. Figure 9 shows the fire prevention trend of next-generation power sources.

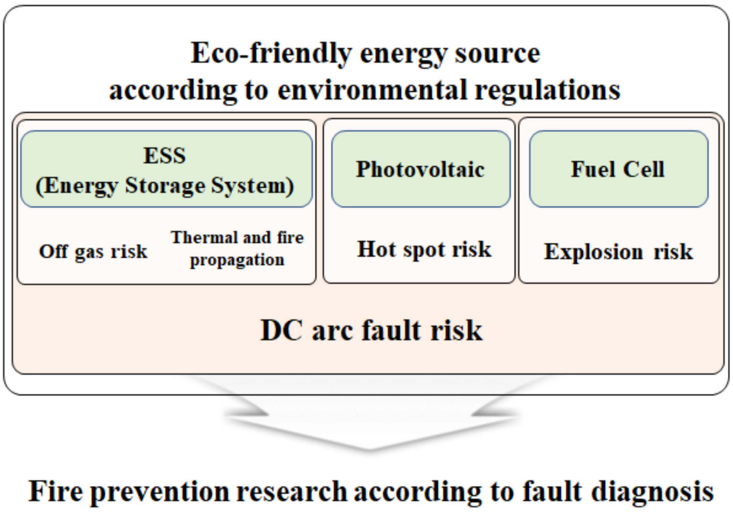

Figure 9. Research trends for fire prevention in next-generation power sources.

3.3.1. Research Trend Analysis for Fire Prevention in Photovoltaics

Laukamp et al. [51] investigated 180 fires that occurred in solar power generation systems and researched the causes. They found that component failure and installation errors were the main causes of fire, and confirmed, by experiment, the fatal risk associated with the DC switch. In addition, Nair [7] showed that there is a high risk of photovoltaics fires, based on the information contained in firefighters' survey reports.

As mentioned above, photovoltaics has a high risk of fire, making it necessary to develop a fire prevention system suitable for the fire characteristics of photovoltaics, as it is very different from the existing systems. Manzini et al. [52] conducted research to create and improve a test protocol designed to analyze the characteristics of fires, as there was no standard suitable for photovoltaic fire characteristics at that time. Falvo and Apparella analyzed the relationship between faults and protective measures by comparing the safety performance of photovoltaic design solutions provided by international standards. They also found that faults occurred in the blind spot of ground fault protection devices by comprehensively analyzing the existing grounded photovoltaics system in the U.S., and emphasized that checking all possible failure modes at the design stage is critical [53,54].

Guerriero et al. [55] proposed a method of blocking a circuit wirelessly when a fire occurs in the photovoltaics system. Their method entailed breaking the circuit in a solar panel, and they verified its suitability through experiments. In addition, Wu et al. [56] emphasized that it is important to reduce the hot spot effect and DC arc, in order to minimize the risk of photovoltaic fire. To decrease the hot spot effect, they introduced three types of techniques for detecting the arc by controlling the space between the photovoltaics modules and reducing the DC.

The fire prevention analysis of photovoltaics was conducted in the direction of experimentally verifying the risk due to component failure and installation error, and minimizing the risk of fire by preventing failure [7,51–54]. Research on ways to reduce the hot spot effect and DC arc has been conducted, as well as research on the application of protective devices that can short-circuit when a failure occurs [55,56].

3.3.2. Research Trend Analysis for Fire Prevention in Energy Storage Systems

As the energy storage systems devices used to store energy are electrochemical devices, they have completely different fire characteristics from existing electrical devices. It is necessary to develop a prevention system, since the gas emissions generated from charging and discharging an energy storage system can cause fire and explosion. In particular, when a fire occurs in an energy storage system, the temperature of the electrolytes also rises and additional fires can break out, which in turn can lead to thermal runaway and enormous damage. Researchers have analyzed the characteristics of the thermal runaway fire of energy storage systems through experiments and researched methods of preventing fire and thermal runaway by diagnosing energy storage system failures.

Larsson et al. [57] defined six cases caused by the abuse of a lithium-ion battery and conducted experiments to analyze the characteristics of these fires. They reported that higher reactivity was obtained when SOC (state of charge) was in a high state, rather than a low one, and found that HF (hydrogen fluoride) increased instantaneously when water mist was sprayed during a fire. However, the amount of total HF released was the same, suggesting that further research is needed to extinguish the fire with water.

Chen et al. [58] analyzed the characteristics of fires based on experiments using multiple LIBs (lithium-ion batteries) and discovered the characteristics of the continuous acceleration of thermal and fire propagation. They also analyzed the effects on the speed of thermal and fire propagation by measuring the impact pressure. Ping et al. [59] summarized the characteristics of fires by running a full-scale burning test of a 50Ah lithium-ion battery, which was burned through the processes of battery expansion, jet flame, stable combustion, second flame jet, stable combustion, and third flame jet. The results of the analysis showed that the high temperature during combustion was caused by a short circuit inside the battery.

Experimental research has also been conducted to analyze the thermal runaway characteristics of the lithium-ion battery. Huang et al. [60] analyzed the thermal runaway based on its thermal characteristics and flame spread of a lithium-ion battery through experiments. In addition, Li et al. [61] proposed a guide for safety design by conducting experiments to analyze the mechanism behind thermal runaway propagation and the effect of SOC (state of charge) on thermal runaway.

Meanwhile, Wang et al. [6] reviewed the failure mechanism of the lithium-ion battery. They claimed that the failure characteristics can differ, depending on the electrodes and electrolytes of the battery, and that thermal runaway occurs due to SOC (state of charge) and abuse conditions. They also reported that fire and thermal runaway tests of large-scale LiBs can be used to secure a safe design and establish a standard and that appropriate simulation can be a cost-effective substitute for large-scale tests. Mao et al. [62] concentrated on the nail penetration test to analyze the characteristics of fires caused by an internal short circuit among failure mechanisms. They proposed a "micro short-circuit cell" for analysis and found that the thermal runaway response varied depending on the penetration location, depth, velocity, and SOC (state of charge).

Research has also been conducted to develop and demonstrate a failure diagnosis mechanism to prevent fires based on the thermal runaway characteristics of the battery. Gao et al. [63] concluded that battery fires are caused by an internal short circuit and that battery overcharging is a potential cause of internal short circuits. They proposed the use of a unique voltage drop pattern to detect internal short circuits and found that it can be used to prevent fires at the early stage. Ma et al. [64] investigated the fault characteristics of the parallel-connected battery pack and developed a method of identifying connection faults and internal resistance increase faults. They used estimated resistance, tap voltage, and temperature values for fault identification. Alternatively, Yang et al. [65] proposed a method of diagnosing soft short-circuit faults based on the EKF (extended Kalman filter) and verified by experiment that their method quickly detected faults.

Paul and Chang [66] designed and analyzed a flux-modulated permanent magnet linear actuator for detecting fires in energy storage systems. They analyzed its performance using an optimal model and developed a prototype by conducting an FEA (finite element analysis). Schmid et al. [67] conducted research aimed at diagnosing failures based on data, in order to detect latent defects at an early stage before the occurrence of thermal runaways. The researchers detected abnormalities by comparing cells and devised plans to improve reliability by combining various sensor types.

Unlike general fires, an energy storage system has thermal runaway fire characteristics, with experiments being conducted to analyze it. Thermal runaway experiments were conducted according to affective factors (state of charge, impact pressure, etc.), while mechanisms were analyzed based on the test results [57–61].

An experimental study was also conducted to analyze the fire characteristics for failure conditions. Data on fire characteristics were provided through studies applying electrical and physical fault conditions. In addition, research for fault diagnosis was conducted based on fire characteristic data, and experimentally confirmed fault detection [6,62–67].

3.3.3. Research Trend Analysis for Fire Prevention in Hydrogen Fuel Cells

Since hydrogen fuel cells do not emit any environmental pollutants, they are being touted as a next-generation energy source, with efforts being made to apply it to buildings based on development and demonstrations. However, a safety device for preventing fires and explosions should be simultaneously developed and applied, since hydrogen fuel cells pose a high risk. The present study analyzed the research trend for fire prevention in hydrogen fuel cells that carry a risk of explosion.

Zheng et al. [68] conducted research related to the localized fire testing of a high-pressure hydrogen tank by conducting numerical analysis and experiments simultaneously. They analyzed the factors that affect the TPRD (thermally activated pressure relief device) activation time through fire experiments and analysis. Hupp et al. [69] ran a localized fire test of a hydrogen storage tank through experiments and analyzed the effects of fire temperature, the size of the fire suppression area, and the initial hydrogen pressure on fire resistance. Grune et al. [70] conducted experimental research on the release of unstable hydrogen ignited in a high-pressure hydrogen tank, and provided new experimental data on pressure load and thermal emission.

There have been other studies aimed at detecting leaks from high-pressure hydrogen tanks at the early stage or at reducing the risk of fire and explosion in the event of an accident caused by a leak. Maeda and Tamura [71] conducted research on detecting leakages from tanks based on hydrogen leak noise. They collected hydrogen leak sound data using helium as an alternative gas and determined the critical flow rate required to identify a hydrogen leak in a real environment. Tamura et al. [72] tested the impact of an emergency response, using forced wind after a hydrogen fuel cell accident, and analyzed the forced wind conditions necessary for an emergency response. Although these two studies were applied to a vehicle, the results are deemed to be applicable to the installation location and the type of hydrogen fuel cells used in a building.

Wang et al. [73] summarized the measurement items needed to monitor fires in the hydrogen fuel cell system. They reported that, for the purpose of measurement, it was necessary to collect all the information contained inside the fuel cell system, such as gas concentration, voltage, current, stack temperature, etc., and that the thermal runaway should be detected at an early phase based on such information. Mahanijah et al. [74] developed FDI (fault detection and isolation) of hydrogen fuel cells by combining feedforward and feedback control strategies. They verified the normal operations in a simulation by applying five fault conditions. Furthermore, Zhou et al. [75] performed a simulation of the fuel cell system, applied the leading malfunctions, and compared the results with actual failure data. A database for fault diagnosis could be built for the model and used for subsequent studies.

Fire prevention analysis of hydrogen fuel cells has focused on how to detect a hydrogen leak at an early stage. A method for measuring hydrogen leak sound was proposed as a method for detecting hydrogen leaks. It was experimentally verified that an emergency response effect is possible, using forced wind in the event of a leak. The two studies mentioned were for automobiles, but it is estimated that they can be applied to hydrogen fuel cells for buildings [71,72]. A failure diagnosis study was also conducted for hydrogen fuel cells to prevent fires. Gas concentration, voltage, current, stack temperature, etc., which are important factors, were selected, while a database for diagnosing failure conditions was secured [73–75].

4. Future Research Direction

The main causes of fires in buildings were classified into three categories, and research trends for each cause were analyzed. Many researchers proposed ideas for fire prevention from various perspectives and verified their suitability through simulations and experiments. Based on the analyzed research trends, we propose future directions for fire prevention research. To propose a realistic direction suitable for practical application, the four strategies of Korea's fire safety policy in 2023 were reviewed. The main contents of the four strategies are as follows.

The four major strategies of Korea's 2023 fire safety policy are: first, to improve the fire safety system; second, to create a safe environment; third, to strengthen public fire prevention publicity and education; and, finally, to secure fire safety infrastructure [76,77].

The first strategy (to improve the fire safety system) includes the intensive management of fire safety in logistics warehouses; the preemptive and reasonable regulation of multi-use establishments; the establishment of a safety management system for high-rise buildings; the enhancement of the practical inspection capability of fire facility managers; and the creation of an autonomous safety management system.

The second strategy (to create a safe environment), which is aimed at eliminating safety blind spots, includes the creation of a safe living environment for vulnerable groups in fire safety; the effective implementation of fire safety investigations for large fire concerns; the enhancement of fire prevention and safety management of important national facilities; and the establishment and operation of an IoT-based real-time "Fire Facility Information Management System".

The third strategy (to strengthen public fire prevention publicity and education) focuses on establishing a safety culture in the general public's everyday life through the establishment of a fire safety education system, customized for each life cycle, and the enhancement of fire safety education for vulnerable groups, such as the disabled.

Finally, the fourth strategy (to secure fire safety infrastructure) focuses on expanding infrastructure to improve access to public safety education through the supply of data-based site-specific information; the revitalization of the firefighting industry by expanding the fire safety big database; and the consolidated processing of duties by integrating fire prevention information systems.

In summary, it is necessary to improve fire prevention technology by applying ICT (information and communication technologies), which has developed rapidly in recent years; develop a system that can support decision-making in an emergency response system; and develop and apply appropriate training models by classifying the groups of people who need to be better prepared and trained. Based on these elements, the research direction suggested for fire prevention is as follows.

4.1. Selecting a Detection System Based on Risk Assessment

Various types of detectors are available for installation inside buildings, such as smoke detectors, flame detectors, heat detectors, gas detectors, and video-based image analysis systems. Despite the fact that it might be desirable to install and operate all types of detectors in all spaces, the actual costs of installation and maintenance must be taken into account. Therefore, it is necessary to select and install an appropriate type of detector by correctly determining the characteristics within a given area. Figure 10 shows the method of selecting a detection system through risk assessment.

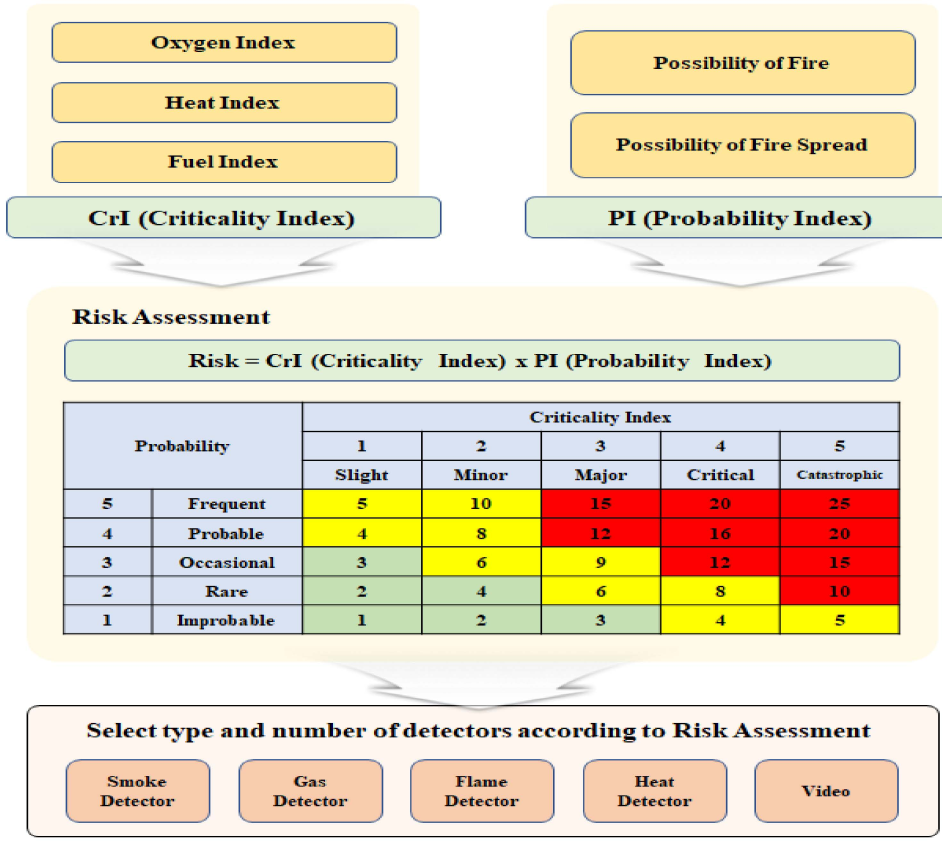

Figure 10. Selecting a detection system based on risk assessment.

To select the appropriate detector, it is necessary to divide the areas in the building according to their characteristics and conduct a risk assessment. Figure 10 shows the proposed risk assessment method, with the details as follows. In the risk assessment, oxygen, combustible materials, and ignition sources, which are the three elements of combustion, are defined, and 1 to 5 points are assigned to each. The Oxygen Index defines the concentration of combustible gas in the air that can be formed by leaking gas, while the Heat Index defines the level of an ignition source that can cause a fire, and the Fuel Index defines the combustible concentration range of the gas used. Three to 15 points obtained by summing up the points given by the three indexes are converted into 1 to 5 points. The corresponding score is defined as the CrI (Criticality Index).

In addition, the PI (Probability Index), which is an indicator of the possibility of occurrence and spread of fire, is defined. The PI is calculated by the FI (Fault Index), which indicates the possibility of fire occurrence, along with the SI (Spread Index), which indicates the possibility of fire spread. The FI defines the possibility of a fire caused by a defect on a scale of 1 to 5, while the SI defines the possibility of a fire spreading on a scale of 1 to 5. The PI is defined by converting 1 to 25 points obtained by multiplying the two indicators into 1 to 5 points.

Determine the final risk by applying the CrI and PI to a commonly used 5×5 matrix. Based on the risk, the number of gas detectors required in the zone is selected.

In risk assessment, the Fault and Spread Indices, which belong to the Probability Index, can reduce risk through action. To reduce the risk of the corresponding indicator, basic research on fire from ignition sources is required, with a need to address this in future studies. Specifically, a database should be secured through conditional experiments on specific ignition sources, along with reduction plans to be suggested through data analysis.

4.2. Improving the Reliability of the Detection System

The important thing in the detection system installed through risk assessment is the reliability of the measurement. This is important for two following reasons. Fire can be prevented at an early stage by increasing the accuracy of early fire detection, and confusion among building residents prevented by reducing false alarms. Research directions to increase the reliability of measurement were presented from two perspectives, and are shown in Figure 11.

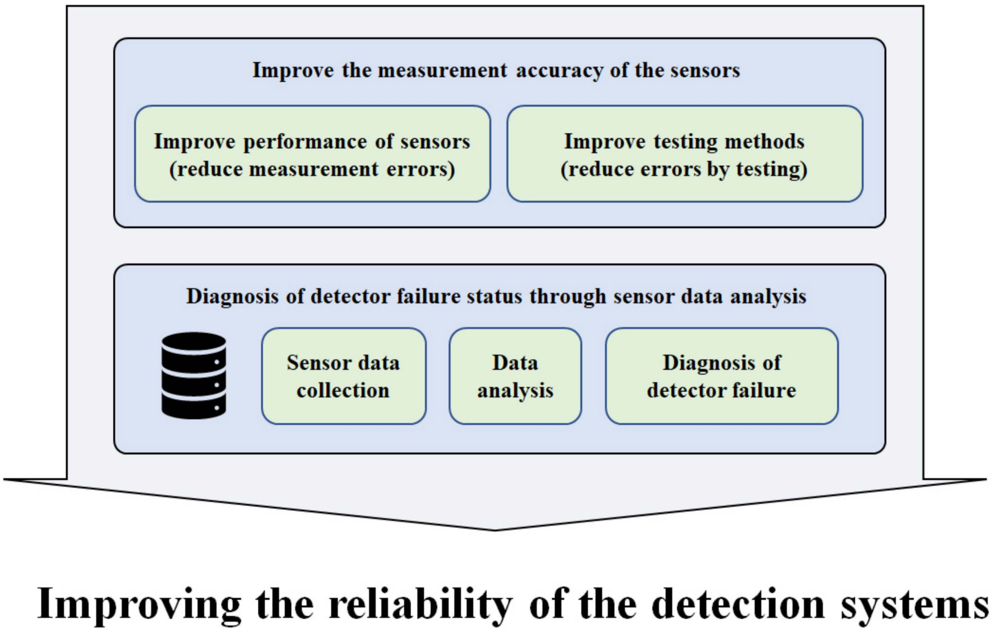

Figure 11. Improving the reliability of the detection system.

There are two main approaches to improving reliability. One involves increasing the measurement accuracy of sensors, while the other is analysis based on the measured data. First, one must consider improving the performance of the sensor itself or empirically testing the sensor to increase its measurement accuracy.

To increase the measurement accuracy of the detector itself, additional research in the sensing system field is required, and the research goal should be to exceed the best performance given by the type of detector. In addition, existing detector performance evaluation methods should be reviewed, along with factors that may affect measurement accuracy being identified. In particular, research is needed to propose an evaluation method that can simulate the actual installation situation, as opposed to the simple performance evaluation method of the detector.

However, despite this increase in measurement accuracy, false alarms may occur due to disturbances in real-world applications, aging equipment, and so forth. More studies are needed to prevent false alarms due to such factors—for instance, by determining a false alarm through measured data analysis, or by diagnosing the failure state of a detector by analyzing data.

4.3. Operating a Fire Prevention and Control System

It is necessary to develop and apply a control system that can generate an alarm if a fire is detected and to devise a plan for evacuating the occupants of the building in the event of a fire. That is, a system is needed that can actively establish an evacuation and escape plan that considers both the residential and fire hazard areas. In particular, this type of system will become increasingly important as buildings become ever taller and more complex; therefore, it is necessary to consider this system from the design stage, encompassing the characteristics of each building. Figure 12 shows an example of operating a fire control system.

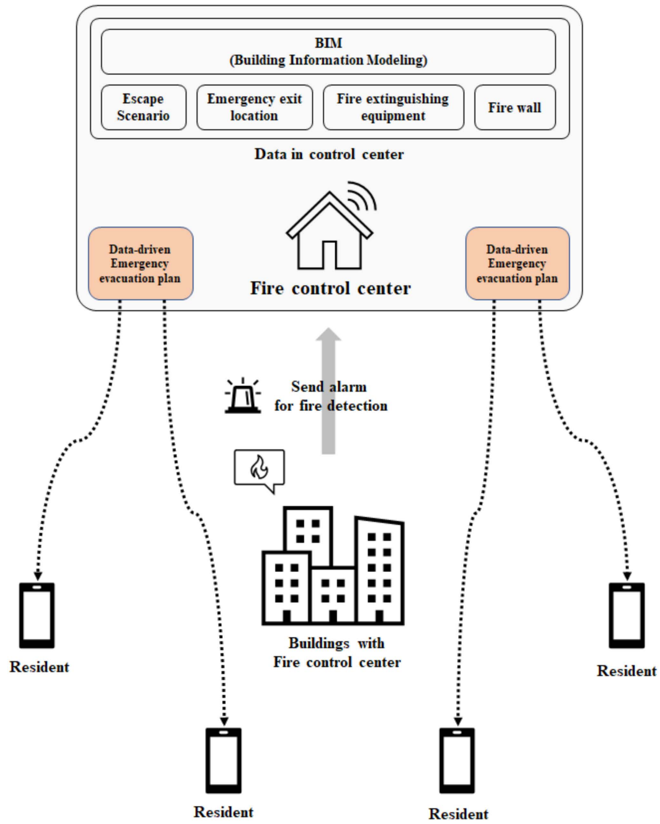

Figure 12. Sample operation of fire control center.

When designing a fire prevention control system, the operation and status of fire extinguishing equipment should be checked, including the above detection system. Such equipment includes portable fire extinguishers, fire sprinklers, fire pumps, and firewalls, but a method of escaping the building safely, based on the locations of the building's emergency exits designed, should also be included.

In addition, BIM (Building Information Modeling) should be used together to increase building safety and disaster response capabilities, rather than operating the system using only the information generated from a given building [78]. The emergency response information created by the integrated control system can be transmitted via wireless communication, using a personal device or IoT (Internet of things) function installed in the building, and be used as a system for safe evacuation in the event of a disaster. Actual research in this area has been reported [79], but the system needs to be applied to the residents of all buildings to ensure safety.

4.4. Reinforcing Safety Training for Fire Prevention

From the perspective of fire prevention, it is also important to train the residents of buildings, in addition to providing the infrastructure for fire prevention and emergency response measures. Safety training should include the emergency response procedure; the method of evacuation to follow based on information received from the control center; and the operation of fire extinguishing equipment. It is also necessary to conduct safety training that takes into consideration the characteristics of a building and its occupants. Figure 13 shows a method for effective fire prevention education, and Figure 14 shows a network configuration diagram for fire prevention education.

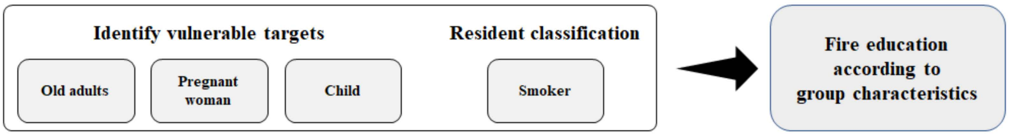

Figure 13. Reinforcing Safety Training for Fire Prevention.

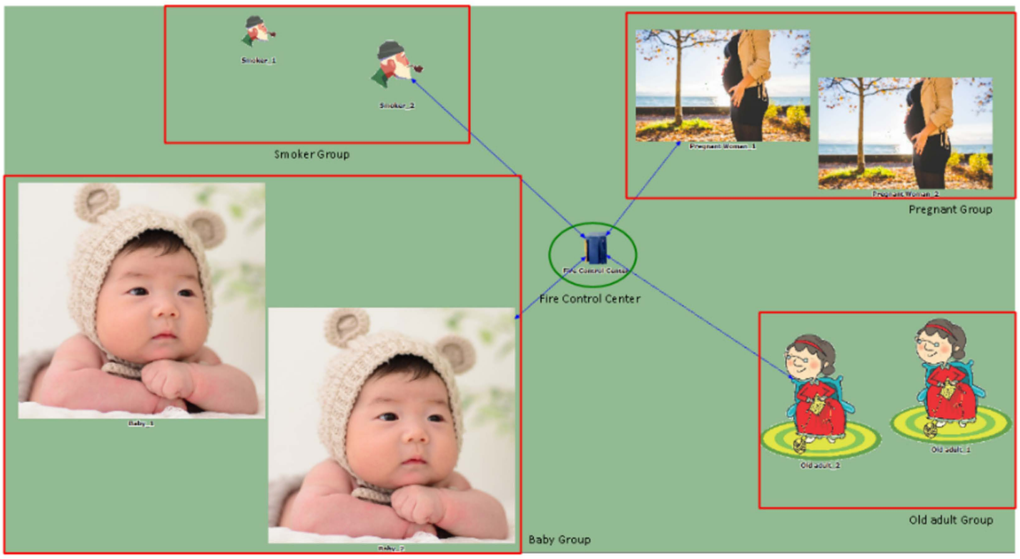

Figure 14. Network configuration map for reinforcing safety education for fire prevention.

Many international studies have attempted to find ways of identifying vulnerable persons who require fire safety training and training the occupants of buildings according to the proposed classification. There have been many studies aimed at either developing a necessary training model for older people who are vulnerable to fire [80], or developing an effective method of training specific vulnerable groups [81,82], as well as defining different population groups and conducting effective fire safety training [83]. In addition to the existing research results, it is necessary to select more data for consideration and to develop and diffuse a training program that reinforces fire safety awareness. Figure 15 shows an example of reinforcing safety education. It shows the fire education plan for the Smoker group, which is vulnerable to fire, and it is an emergency response system based on group information.

Figure 15. Information communication for reinforcing safety education for fire prevention.

5. Conclusions

This study presents the results of an analysis of related research trends, and proposes future directions for research on preventing fire accidents, which occur with increasing frequency each year. First, the location and cause of the fire were selected to analyze related research trends. Based on the analysis results of fire statistics data in Korea, the building, which is the place where most fires occur, was selected, and the classification of research trends according to three main causes was selected. The three topics for research trend analysis are as follows: prevention of fires by fire and gas detection; prevention of fires in electrical appliances; and prevention of fires in next-generation electricity.

Based on the analyzed research trends, future research directions for fire prevention research were suggested. To propose a direction suitable for real-world application, the four strategies of Korea's fire safety policy in 2023 were also reviewed and reflected. The main content of the proposed research direction is to apply ICT (Information and Communication Technologies) to improve fire prevention technology and improve related infrastructure. Four research directions were suggested, and they are as follows.

First, a detection system must be selected based on risk assessment. To evaluate the risk, the Criticality Index was calculated based on the Oxygen Index, Heat Index, and Fuel Index, and the final risk was evaluated by reflecting the Probability Index. The number and type of detectors must be selected in consideration of the evaluation results. This method will be helpful in constructing an efficient infrastructure.

Second, the reliability of the detection system must be improved. Methods of improvement include improving the measurement accuracy of the sensor itself and improving measurement accuracy by analyzing measurement data. To improve the accuracy of the sensor itself, a sensor module for reducing measurement error should be developed, and a method for reducing measurement error by performance test of the sensor should be proposed. In addition, a research direction to increase measurement accuracy through data analysis techniques is proposed. This research direction will contribute to improving the reliability of infrastructure.

Third, a fire control center that detects and controls fires in buildings must be established. This is a system that operates a center based on BIM (Building Information Modeling), escape scenarios, fire extinguishing equipment, etc.; actively establishes an emergency response system; and informs building residents. This research direction, which incorporates AI technology, will contribute to improving fire prevention technology.

Fourth, it is critical to strengthen safety education for fire prevention. The target of safety education must be identified, and a training process and contents specialized for the target must be established. This research direction will enable effective educational performance.

As a result, it is estimated that this paper will enable researchers to identify research trends in accordance with the causes of fires and select the direction of future studies.

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